BUNCH-SHAPE MEASUREMENTS AT PSI'S HIGH-POWER CYCLOTRONS AND PROTON BEAM LINES

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Abstract

Longitudinal-transversal 2D-density distributions of the bunched 2.2 mA CW proton beam can now be measured at the 13 last turns of the Injector 2 cyclotron, at several locations in the connecting beam line to the Ring cyclotron, at the first two turns of the Ring cyclotron (all at energies around 72 MeV), as well as behind the Ring cyclotron (at 590 MeV). In the large part, distributions can be taken from several angles of view, separated each by 45°.

The measurement systems at our facility have evolved with time; this paper gives the present status, performance, limits and typical results. Due to the limited space, we refer in the large part to our previous publications [1, 2, 3] and concentrate on recent findings and measurements and ideas for next steps.

INTRODUCTION

In contrary to its predecessor in 1992 [4], the "old" detector setup (Fig. 1a) operating in 2000 [1] already had a time resolution allowing to resolve the bunch time structure at the last two turns of Injector 2. Since 2004 it is (with a single detector) also used in the Ring cyclotron [5]. The "new" detector setup from 2010 [2, 3] provides a larger count rate and thereby much shorter measurement durations. Here it was intended to again allow the determination of time resolution, but by a simpler design [2]. This failed as is discussed later.

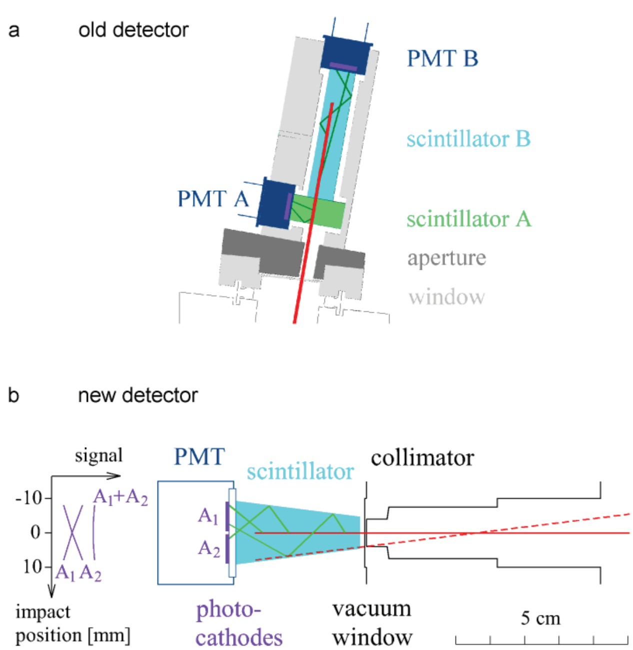

Figure 1: a) Old detector setup (at RIZ1). b) New setup.

The evaluation procedure with several corrections is described in [3] and the background correction needed for the measurement in the Ring cyclotron in [2]. Bunch shapes measured at full beam current at all locations are presented in [3]. (Here we have to note, that at the location MXZ1 shortly after the Injector 2, the wire 0 is not melted by a too dense beam as assumed in [3]. Unchanged, this measurement is now operational. The reason for the repeated wire failure is not clear.)

PULSE HEIGHT SELECTION

Protons are scattered elastically at the wire or inelastically, loosing discrete energies, or other particles are created with an energy spectrum. The time-of-flight from wire to detector is different for these species, as well as the photo-multiplier tube (PMT) output pulse heights generated. Pulse-height selection allows to derive the timing information from only a single species. At present, pulse height selection and timing both use leading-edge discriminators (LED) [2], accepting pulses above a certain height. Both discriminator levels are set fixed. The pulse height is adjusted by varying the PMT gain via the PMT voltage while observing the bunch time structure with the wire placed at a fixed position in the beam.

Significant differences in discrimination characteristics are visible for different detectors, locations and beam energies. At ~72 MeV (Fig. 2a-c), the signal is a folding of the bunch shape with the (much sharper) peak structure resulting from the different delays of elastically (left peak) and inelastically (following peaks) scattered protons. The diagonal slope results from discriminator walk at the changing pulse height. To the right, the increase of accepted counts with the PMT voltage is depicted. The steps due to the species with different energy loss are visible. The blue line marks the level, where all elastically scattered protons are accepted. To the far right, the 1σ-length of the distribution is displayed. The red line indicates the voltage level, which gives a good resolution and, if possible, allows the use of all elastically scattered protons. The protons are stopped in the scintillator, a sharp step in the count rate of the elastically scattered protons (ESP), which give the highest pulses, is expected, when a certain voltage is surpassed. This is the case at Fig. 2a,c and with all ESP utilized, the displayed bunch length is still minimal. In contrary, at Fig. 2b there is a gradual increase, the pulse heights seem to be "smeared out". Here not more than ~40% of the ESP can be used without increasing the measured bunch length. The reason for this is not clear. Possibly, the stronger coupling of RF noise to the PMT base-line signal observed in this case plays a role. The old detector (Fig. 2a) exhibits a linear walk while the new detector

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(Fig. 2b, c) shows a “hook”. This may be an effect of the detector geometry.

At the 590 MeV location (Fig. 2d), two species are visible with discrete defined upper pulse heights, allowing the same pulse selection scheme, which uses only the highest pulses, to be used. However, the increase of count rate with PMT voltage is not a step but very gradual, caused by a broad energy distribution. Together with the small scintillator, the count rate is very low and hence the measurement duration is long. The red line indicates the practically used voltage level at which only a single species (possibly He^{+}) is accepted. To improve this, we intend to use a delta-E discriminator, which selects a narrow range of pulse heights, together with a somewhat larger distance to the detector which allows the time profiles generated by the two species to separate in time.

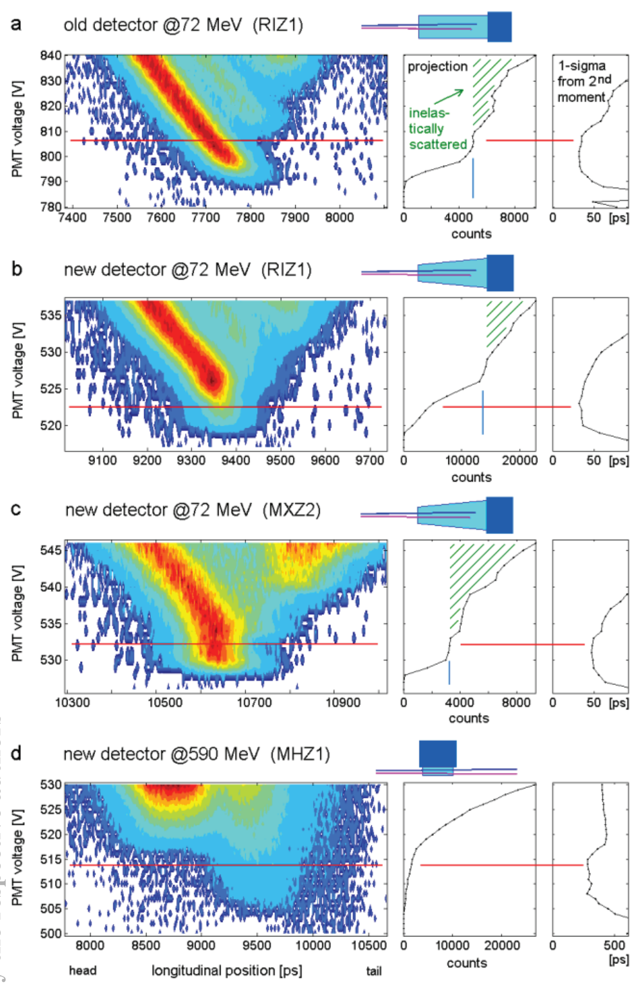

Figure 2: Dependence of measured bunch time profile on PMT voltage with different detector setups.

At locations with significant radiation levels, a degradation of the scintillator (but not of the PMT) was observed. The required PMT voltage increases by e.g. ~2 V per month or faster if the beam is not well tuned. Hence, it must be determined frequently by a voltage scan.

TIME RESOLUTION

At 72 MeV, with the old setup, the time resolution of the larger detector has been determined to $\sigma_{\text{det B}} = 13$ ps from the coincidence spectrum of the arrival times of the elastically scattered protons at two detectors [1] (17 ps with the scintillator degraded by radiation damage).

It was intended to adapt this concept with the new detector by using two photo-cathodes of a single PMT instead of separate PMTs. We have learned that this is not working. The reason is illustrated in the following.

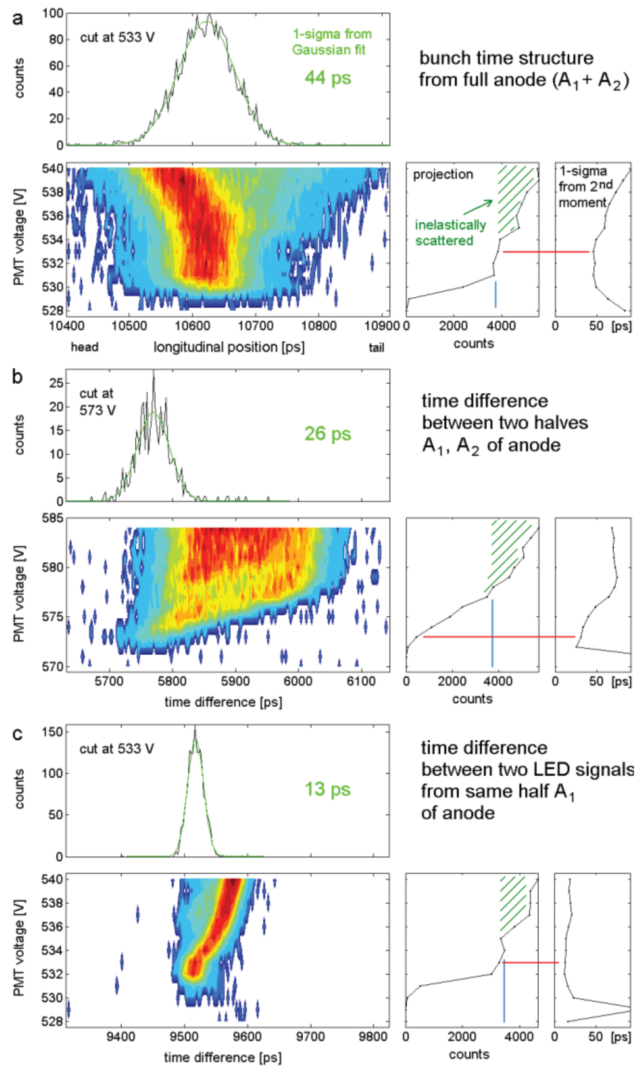

Figure 3: Time spectra taken at 72 MeV with the new detector (MXZ2) at different configurations of the timing electronics (at a fixed wire position).

With the standard bunch time-structure determination (Fig. 3a), in a sharp step of 2 V all ESP are accepted, the bunch length does not change at the adjacent plateau. When measuring the time-resolution with a coincidence measurement (Fig. 3b), the same increase extends over 5 V. In parallel the spectrum width increases strongly, even far above the determined bunch length. This can be explained with the help of Fig. 1b: At low voltage, only protons which impact far at the side of cathode A_1 and give the highest pulses there are accepted by the pulse height selection. This coincidences with the lowest pulses from cathode A_2. (The two signals are not statistically independent as required.) The variation of pulse height is small and with it the discriminator walk and hence the spectrum width. With increased voltage, the spatial confinement of the impact positions is relaxed and the spectrum broadens. Fig. 3c shows the time resolution of the electronics alone including the LEDs which trigger at different relative heights of the same half-cathode pulse. (The time shift with voltage is due to the different walks.) Here the spectrum width is nearly independent from the voltage. Not shown is the case of the electronics without the LEDs, which results in a spectrum width of 10 ps.

It is worth to look at this again. The sum signal from both halves of the cathode is quite independent from the impact position of the proton. This can be concluded from the steep increase in Fig. 3a, as well as from the very short bunch length observed at low beam currents [3]. Hence, then the time resolution is good (but we don't know exactly how good). If there still remain some differences of pulse height with the impact position, caused by the geometry or by local cathode quantum efficiency variations, this results in a systematic error, which is not cured or affected by increasing the number of photo-electrons contributing to the measurement. On the other hand, a reduction of count rate by accepting only the highest pulses can overcome such systematic errors. In this manner, the gradual increase in Fig. 2b and the restoration of time resolution by lowering the PMT voltage may be explained. In general, this is an argument for making the detector as small as possible. (As far as the count rate and the need to stop the particles allow it.)

For the new detector at ~72 MeV, a lower limit for the time resolution can be deduced from Fig. 3c to $\sigma_{\min} \approx 13\ \text{ps}/\sqrt{2}/\sqrt{2} = 6.5\ \text{ps}$, which is the time resolution with scintillator and PMT (local variations of quantum efficiency or gain) exempted, extrapolated to the (double) signal height of the full cathode. An upper limit is given by the shortest measured bunch length of 17.2 ps [3].

At 590 MeV the time resolution has not been clearly determined.

DYNAMIC RANGE AND SENSITIVITY

In an environment with relatively small beam losses and radiation background and with the protons stopped in the scintillator, the dynamic range of the transversal profile taken with the bunch-shape measurement can be extended to ~10^5 (Fig. 4a). Also informative is the sensitivity, defined as the beam current passing through the wire which corresponds to a single count in the integration time at a single wire position. It is 2 nA respectively 47 pA for the conditions of Fig. 4. This is a fraction of 9e-7 respectively 2.1e-8 of the full beam current. Both parameters are limited by the low count rate and the available measurement time. On the other hand, in the longitudinal direction, the limitation is set by artefacts. E.g. it is difficult to confirm that the thin cloud of counts (~0.5% of full intensity) following the main bunch [3] is not an artefact from the counting electronics.

With a high radiation background (as in the Ring cyclotron), artificial background counts set more strict limits. An example is given in [2]. (There however, the degradation of the scintillator by radiation damage played also a role.)

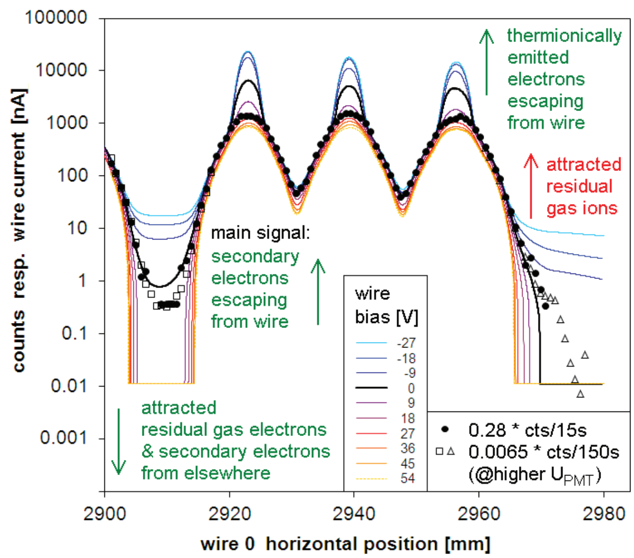

Figure 4: Radial profile of the last three turns of Injector 2 at a beam current of 2.2 mA. a) Bunch-shape measurement (RIZ1, wire 0) with standard integration time 15 s per position (filled circles, ~45000 counts per turn at step width 0.8 mm) and repeated in the low-intensity regions with a 10 times longer integration time (triangles, rectangles, scaling adapted ad libitum). Here in addition the reference PMT voltage was increased from 526 to 540 V giving additional signal from inelastic scattered particles (increase by a factor 4.3). At the dedicated outer tail measurement (triangles), the PMT voltage was not decreased with radius in order to stay sensitive for protons of more than ~59 MeV. b) Wire scans with wire current measurement performed subsequently with the same wire at several wire bias voltages (lines). The wire speed was only 5 mm/s. The wire bias was generated by a switched stack of 9 V cells inserted in the signal cable in front of the electronic module. The base line stems from the ~10 pA lower current limit of digitization.

WIRE PROBE WITH CURRENT READOUT

Most of the bunch-shape monitors allow also for wire current measurements, however, only with a slow wire speed. A direct comparison of both techniques with the wire biased to different potentials allows to study the effect of the different particles contributing to the wire signal (Fig. 4b).

It is remarkable that the positive bias potential of the wire catches thermionically emitted electrons much better

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than the secondary electrons from the wire, although both are mostly slow. This is probably due to the fact that all the secondary electrons created by the bunch are born in the bunch potential (depth without wire of the order of a couple of 100 V) which pulls them away, while most of the time (i.e. between the bunches) the bias potential retards the thermionically emitted electrons. For the given geometry, a bias of approximately 20 to 40 V is sufficient to fully suppress the thermionically emitted electrons. (In principle, one should be able to conclude from such a measurement to the depth of the space charge potential.)

A thermal simulation of this measurement indicates that the thermionic emission would decrease to ~1% of the regular signal at a wire speed of 1m/s. However, the relatively slow "standard" wire probes at the outer turns of Injector 2 (RIE1/2) and the inner turns of the Ring cyclotron (RRI2) which are not biased will probably be affected similarly.

At signal currents below 10 nA, the depicted wire current at 0V bias seems to roughly follow the profile from the bunch-shape measurement. The theoretical sensitivity, defined as the lowest detectable beam current passing through the wire, is set by detection limit of the electronics and the secondary emission yield to ~0.08 nA. However, in the given environment artefacts from slow electrons and ions (Fig. 4b) play a role: The measured shape of the beam tail is strongly dependent on the direction of wire movement, not reproducible over minutes and somehow dependent on the history of wire movement (not shown). One has to keep in mind that residual gas ions and electrons of e.g. roughly a nA per cm of travel are created by the proton beam at a residual nitrogen pressure of 2e-6 hPa. Also, influence from nearby surfaces which are charged up by the beam or stray particles, can play a role (especially at higher wire speeds).

In the given situation, a dynamic range of profile height of 1000 and an effective sensitivity of 10 nA seems a reasonable assumption for the wire current measurement. In the Injector 2 and in the 72 MeV beam line with a not too high radiation background, the bunch-shape measurement appears to be more accurate than the wire current measurement and can be used as a reference for the latter. Of course, there are possible error sources which affect both methods in the same way, e.g. wire erosion or wire misplacement.

In the cyclotrons, the vicinity of strong RF and magnetic fields can generate further sources of error for both measurements. Especially in the Ring cyclotron at not optimal tuning states (increased losses), large artefacts have been observed locally in the radial probe wire current measurements, which possibly have to be attributed to plasma clouds or surface charging. In the Injector 2 at certain probe locations mutual disturbance of the signals from 3-wire probes have been observed [6]. In the absence of obvious artefacts it is difficult to judge the quality of these measurements.

DERIVED BUNCH PARAMETERS

From the measured 2D density distributions [3] bunch parameters can be distilled, e.g. first and second moments as shown in Fig. 5. (The vertical information is derived from a combination of two measurements.)

Presently, the information from profile monitors, wire probes and bunch-shape monitors is mostly introduced into beam dynamics simulations in this form. However, for a code like OPAL, which tracks particle distributions in detail [7], and with the aim of understanding beam tails and losses in detail, a lot of valuable information is already lost in this step, especially in the case of non-Gaussian distributions.

DATASETS AND LOGGING

The role of detailed simulations in the quest for lower losses and systematic improvement of the performance of our machine has been outlined in [2]. The author believes that it is essential for the predictive quality of the simulations, to include detailed measured profile and loss information, together with information about their accuracy.

A useful starting point for simulations may be to gather as much as possible information on a well-tuned beam. "Complete" sets of measurements have been taken at production current 2200 μA. This includes all bunch-shape measurements, wire and beam-induced fluorescence monitors and radial probes (as far as they can stand the full beam current). By the bunch-shape measurement software also loss monitor and collimator currents, the readings of current monitors, beam position monitors and phase probes and some 500 machine parameters as magnet and RF settings (as well as PMT settings and wire current) are logged during the measurement at every wire position (minimum, maximum and average values).

By this, also the additional losses created by the wires of the bunch-shape measurements are covered. This may serve as well-defined test cases for the simulation of small beam losses.

A "complete" set of measurements takes roughly a full 8-hour shift. A single measurement of good quality takes 6 to 60 minutes. The user-friendliness of the bunch-shape measurement procedure was largely improved but it is still not a routine measurement.

POSSIBLE NEXT STEPS

To improve the signal-to-noise ratio and to shorten the measurement duration at 590 MeV, a second detector, which has to be triggered in coincidence by the particles passing the first detector, is under consideration. Eventually an additional measurement unit will be installed to obtain more information on the last turns of the Ring cyclotron.

At 72 MeV shortly behind the Injector 2 (MXZ1/2), we intend to measure the beam energy to ~1e-3 by making the distance detector-wire variable (by setting the detector on a motorized feedthrough) and taking the time spectra at two different distances.

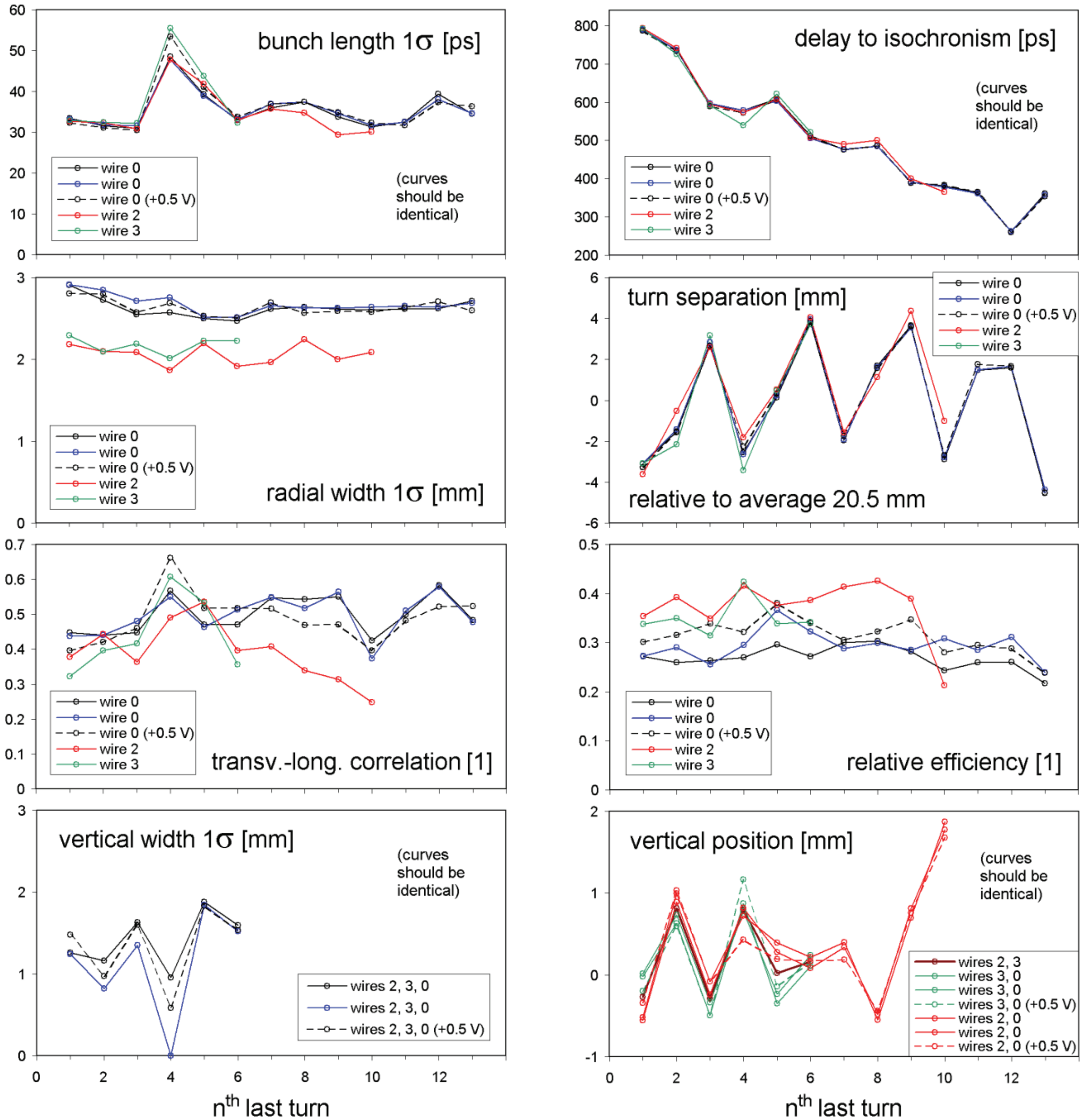

Figure 5: Bunch parameters of the last turns in Injector 2 at the production current of 2.2 mA. (One scan was performed with slightly elevated PMT voltage ramp to see if the discrete 1V-steps of the high-voltage supply play a role. This seems to be not the case. Lines only to guide the eye.)

CONCLUSION

The capability of the bunch-shape measurements at PSI's high power proton beam has been continuously improved. Bunch-shape measurements have regularly contributed to beam development shifts and in a few instances to beam dynamics simulations. Further more detailed simulations of beam transport and losses will rely strongly upon this source of input information and are a strong motivation for continued development.

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